Accurate characterization of metre-sized impactors through casual bolide observations:

Novo Mesto superbolide as evidence for a new class of high-risk objects

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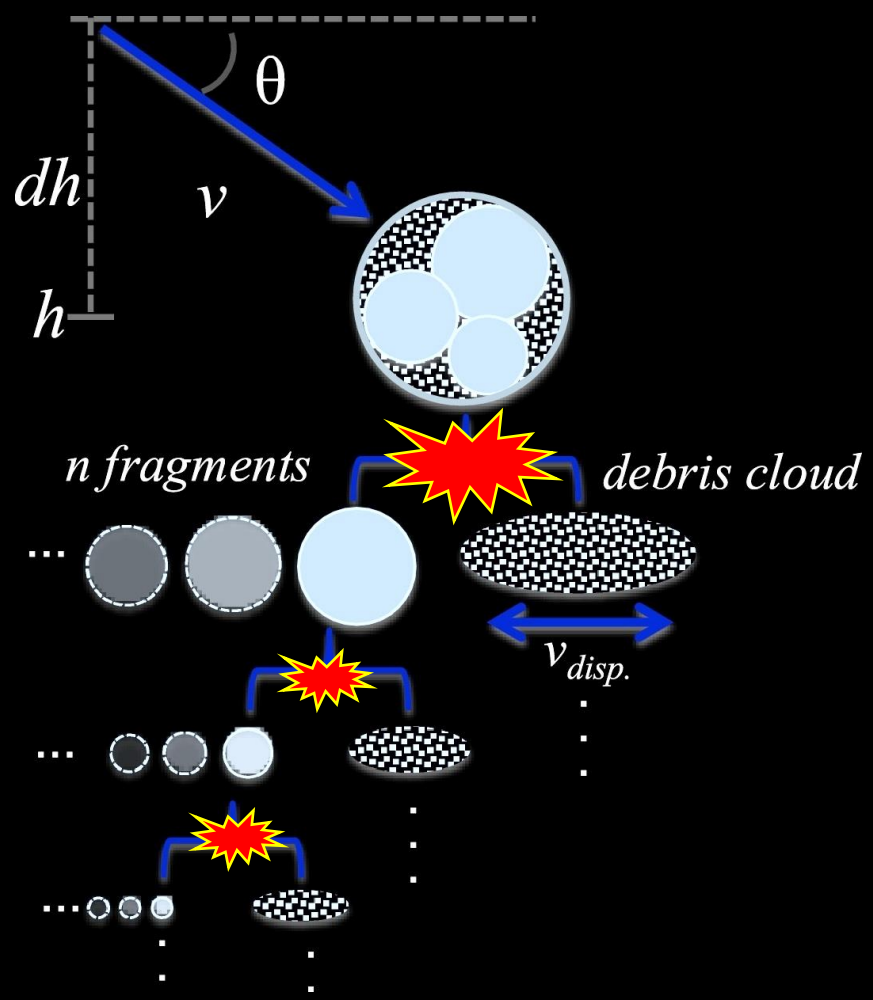
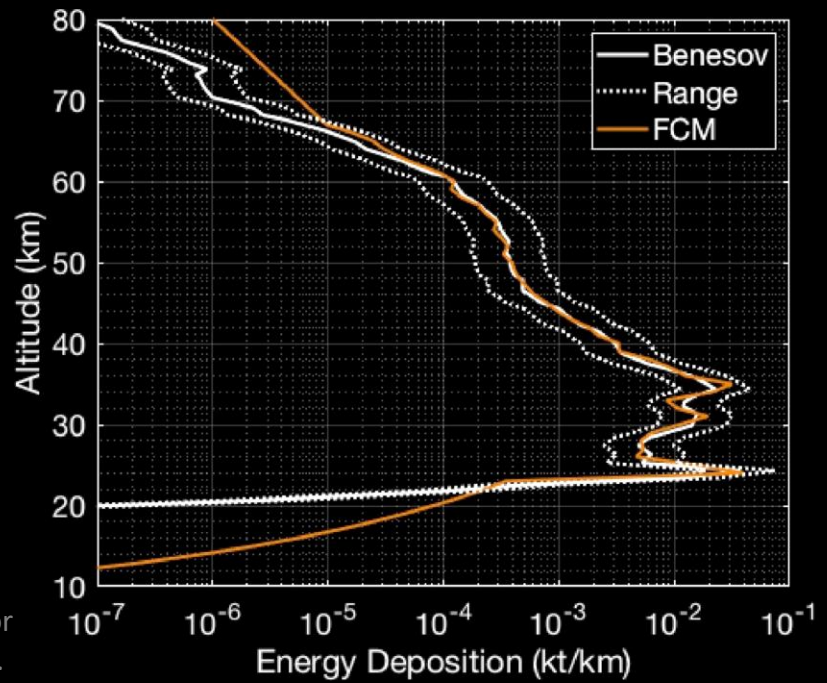
PDC 2023, Vienna

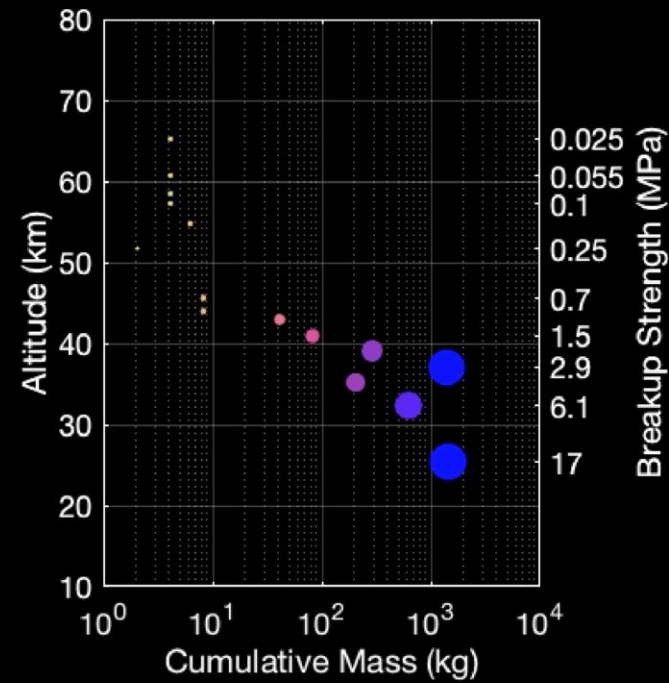
Motivation: Modelling airburst ground effects



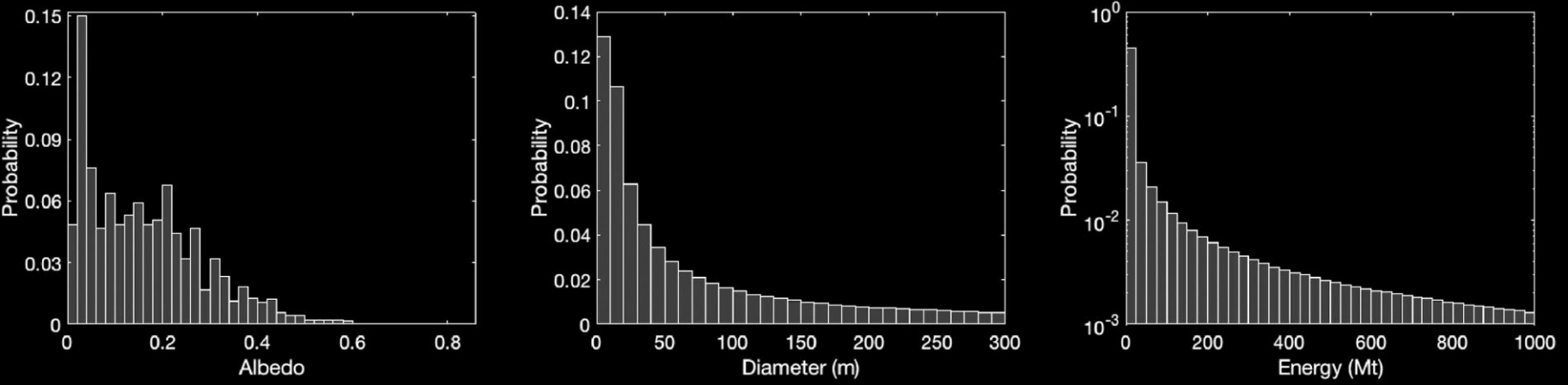
- Assumed strength distribution and fragmentation behavior (Weibull)
- Blast overpressure the main damage source for ≲100 m objects

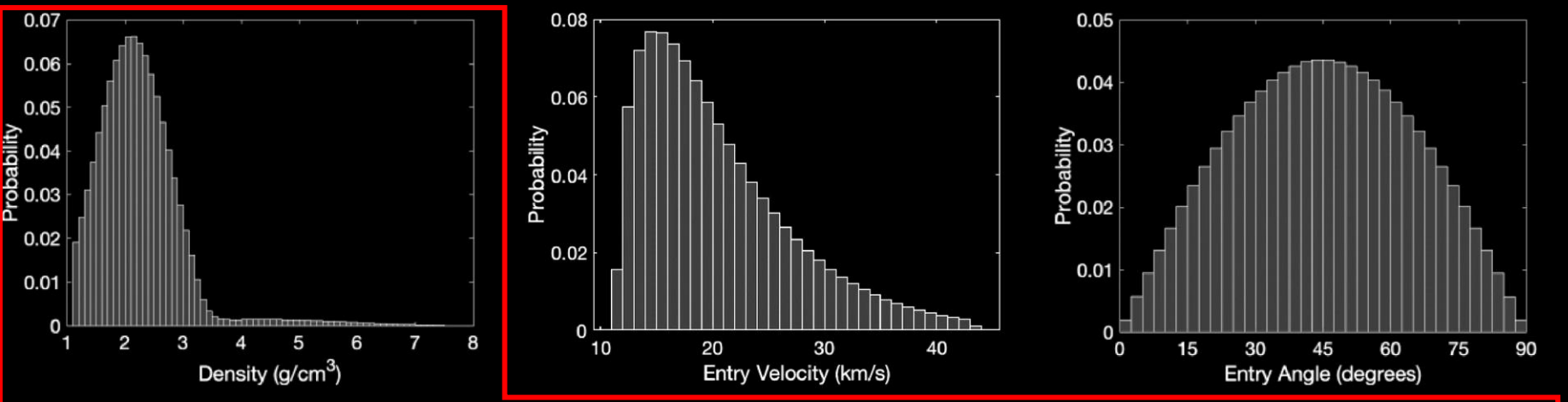
Wheeler, L.F., Mathias, D.L., Stokan, E. and Brown, P.G., 2018. Atmospheric energy deposition modeling and inference for varied meteoroid structures. *Icarus*, *315*, pp.79-91.

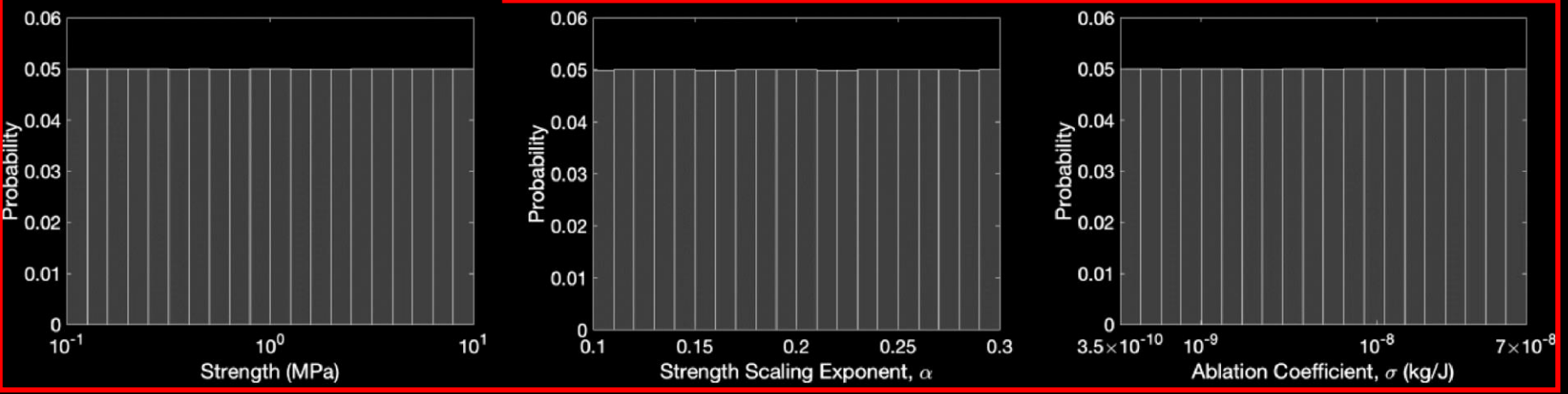




Wheeler, L.F., Register, P.J. and Mathias, D.L., 2017. A fragment-cloud model for asteroid breakup and atmospheric energy deposition. *Icarus*, *295*, pp.149-169.







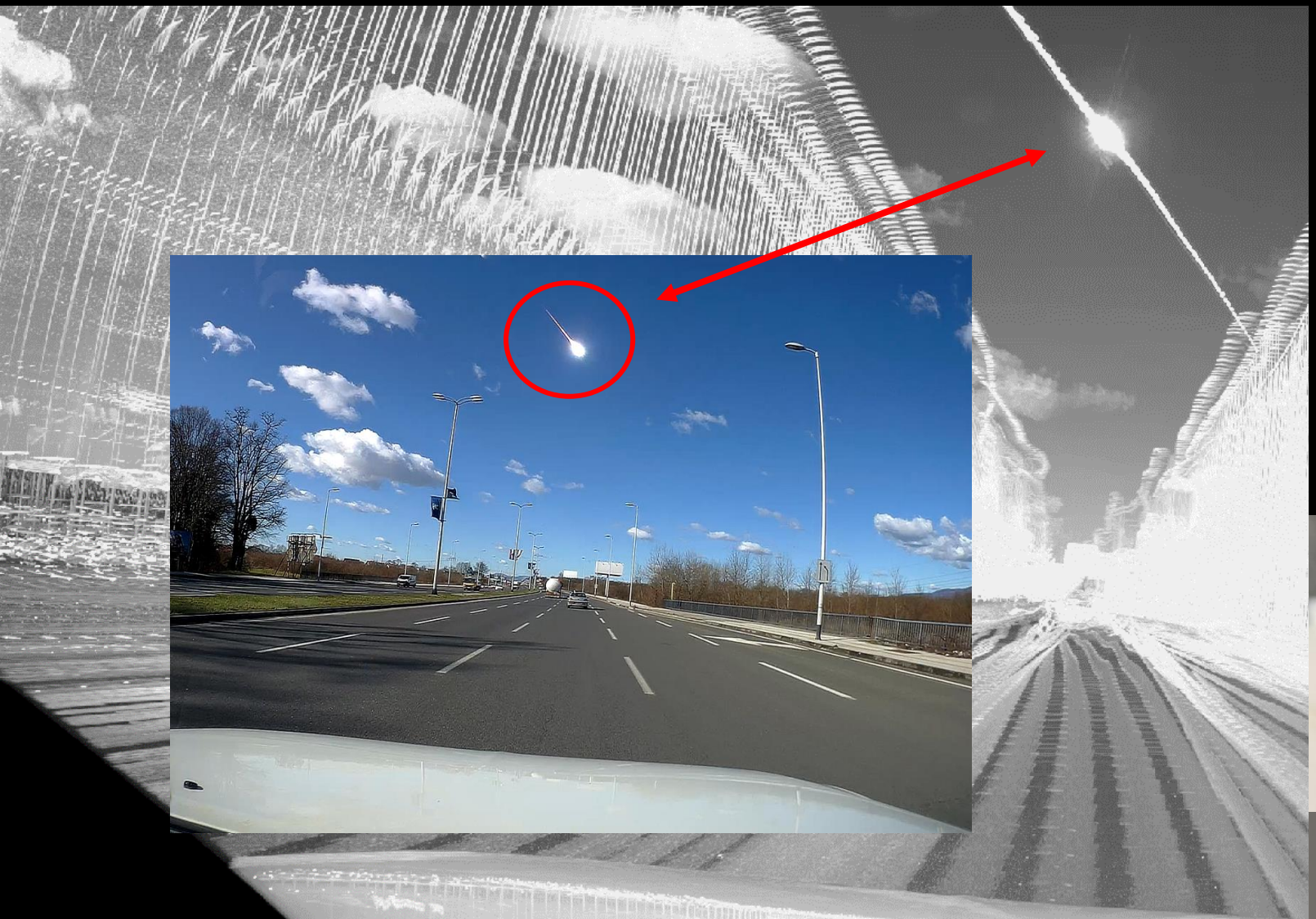
Need observational constraints:

- Dependence of these on orbital class
- Object bulk density
- Strength distribution
- Ablation characteristics
- Fragment mass distribution (small dust vs large fragments)

Wheeler, L.F. and Mathias, D.L., 2019. Effects of asteroid property distributions on expected impact rates. *Icarus*, *321*, pp.767-777.

Novo Mesto (Slovenia) superbolide

- February 28, 2020, 10:30 AM local time



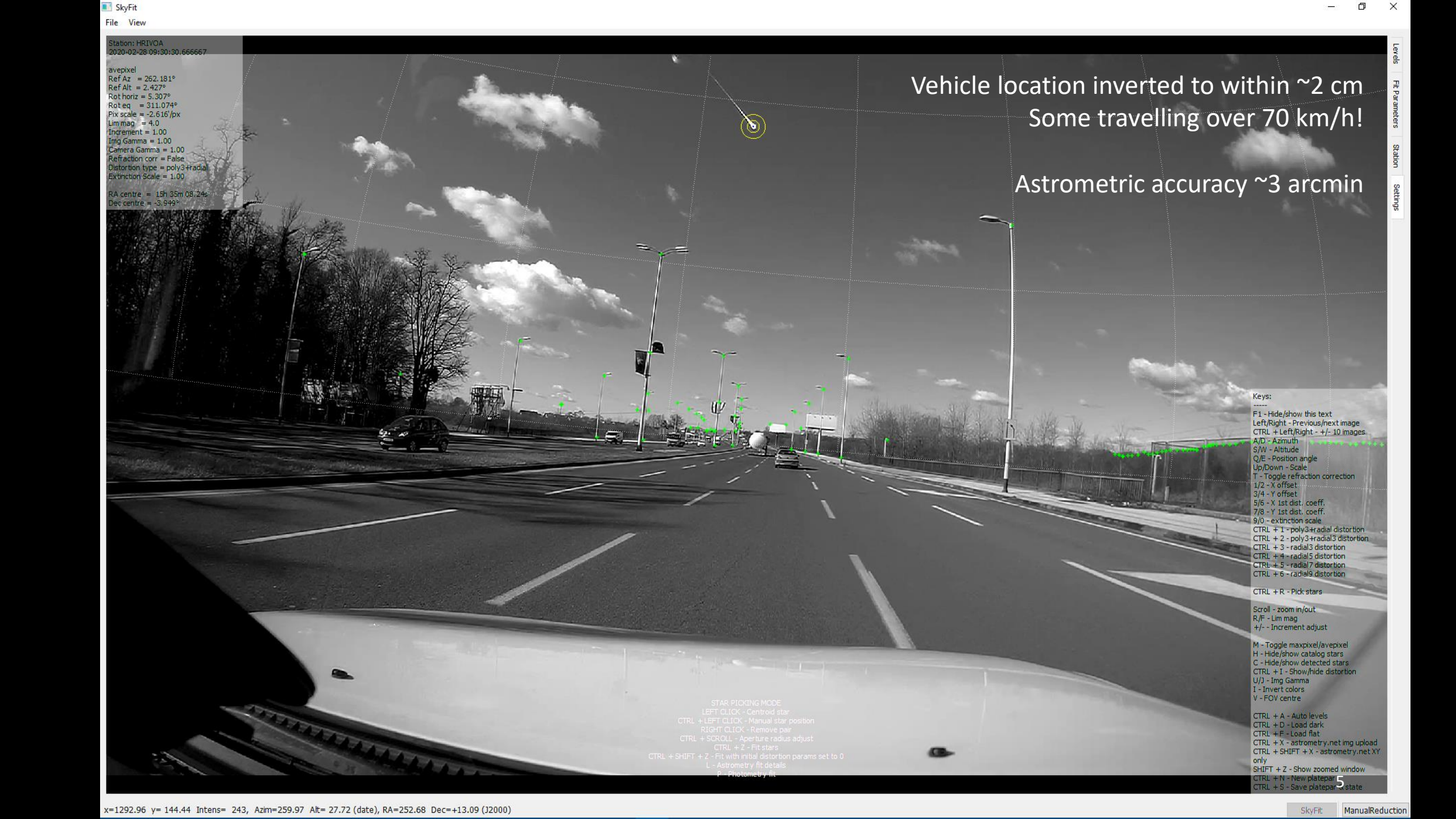
Up to 150 km away:

“loud explosion”

“ground shaking”

“rattling windows”

Three L5 chondrite meteorites (450, 200, 50g) recovered in the following days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File View
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2020-02-28 09:30:30.666667
avepixel
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Ref Alt = 2.427°
Rot horiz = 5.307°
Rot eq = 311.074°
Pix scale = -2.616'/px
Lim mag = 4.0
Increment = 1.00
Img Gamma = 1.00
Camera Gamma = 1.00
Refraction corr = False
Distortion type = poly3+radial
Extinction Scale = 1.00
RA centre = 15h 35m 08.24s
Dec centre = -3.949°
Vehicle location inverted to within ~2 cm
Some travelling over 70 km/h!
Astrometric accuracy ~3 arcmin
Levels
Fit Parameters
Station
Settings
Keys:
F1 - Hide/show this text
Left/Right - Previous/next image
CTRL + Left/Right - +/- 10 images
A/D - Azimuth
S/W - Altitude
Q/E - Position angle
Up/Down - Scale
T - Toggle refraction correction
1/2 - X offset
3/4 - Y offset
5/6 - X 1st dist. coeff.
7/8 - Y 1st dist. coeff.
9/0 - extinction scale
CTRL + 1 - poly3+radial distortion
CTRL + 2 - poly3+radial3 distortion
CTRL + 3 - radial3 distortion
CTRL + 4 - radial5 distortion
CTRL + 5 - radial7 distortion
CTRL + 6 - radial9 distortion
CTRL + R - Pick stars
Scroll - zoom in/out
R/F - Lim mag
+/- - Increment adjust
M - Toggle maxpixel/avepixel
H - Hide/show catalog stars
C - Hide/show detected stars
CTRL + I - Show/hide distortion
U/J - Img Gamma
I - Invert colors
V - FOV centre
CTRL + A - Auto levels
CTRL + D - Load dark
CTRL + F - Load flat
CTRL + X - astrometry.net img upload
CTRL + SHIFT + X - astrometry.net XY only
SHIFT + Z - Show zoomed window
CTRL + N - New platepar
CTRL + S - Save platepar state
STAR PICKING MODE
LEFT CLICK - Centroid star
CTRL + LEFT CLICK - Manual star position
RIGHT CLICK - Remove pair
CTRL + SCROLL - Aperture radius adjust
CTRL + Z - Fit stars
CTRL + SHIFT + Z - Fit with initial distortion params set to 0
L - Astrometry fit details
P - Photometry fit
x=1292.96 y= 144.44 Intens= 243, Azim=259.97 Alt= 27.72 (date), RA=252.68 Dec=+13.09 (J2000)
SkyFit
ManualReduction


SkyFit
File View
Station: HRIVOA
2020-02-28 09:30:30.666667
avepixel
Ref Az = 262.141°
Ref Alt = 2.477°
Rot horiz = 5.297°
Rot eq = 311.089°
Pix scale = -2.616'/px
Lim mag = 4.0
Increment = 1.00
Img Gamma = 1.00
Camera Gamma = 1.00
Refraction corr = False
Distortion type = poly3+radial
Extinction Scale = 1.00
RA centre = 15h 35m 23.49s
Dec centre = +3.941°
Vehicle location inverted to within ~2 cm
Some travelling over 70 km/h!
Astrometric accuracy ~3 arcmin
Levels
Fit Parameters
Station
Settings
Keys:
F1 - Hide/show this text
Left/Right - Previous/next image
CTRL + Left/Right - +/- 10 images
A/D - Azimuth
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CTRL + 2 - poly3+radial3 distortion
CTRL + 3 - radial3 distortion
CTRL + 4 - radial5 distortion
CTRL + 5 - radial7 distortion
CTRL + 6 - radial9 distortion
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RIGHT CLICK - Remove pair
CTRL + SCROLL - Aperture radius adjust
CTRL + Z - Fit stars
CTRL + SHIFT + Z - Fit with initial distortion params set to 0
L - Astrometry fit details
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SkyFit
ManualReduction


SkyFit
File View
Station: HRIVOA
2020-02-28 09:30:30.666667
avepixel
Ref Az = 262.131°
Ref Alt = 2.457°
Rot horiz = 5.127°
Rot eq = 311.260°
Pix scale = -2.616'/px
Lim mag = 4.0
Increment = 1.00
Img Gamma = 1.00
Camera Gamma = 1.00
Refraction corr = False
Distortion type = poly3+radial
Extinction Scale = 1.00
RA centre = 15h 35m 22.03s
Dec centre = -3.961°
Vehicle location inverted to within ~2 cm
Some travelling over 70 km/h!
Astrometric accuracy ~3 arcmin
Levels
Fit Parameters
Station
Settings
Keys:
F1 - Hide/show this text
Left/Right - Previous/next image
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STAR PICKING MODE
LEFT CLICK - Centroid star
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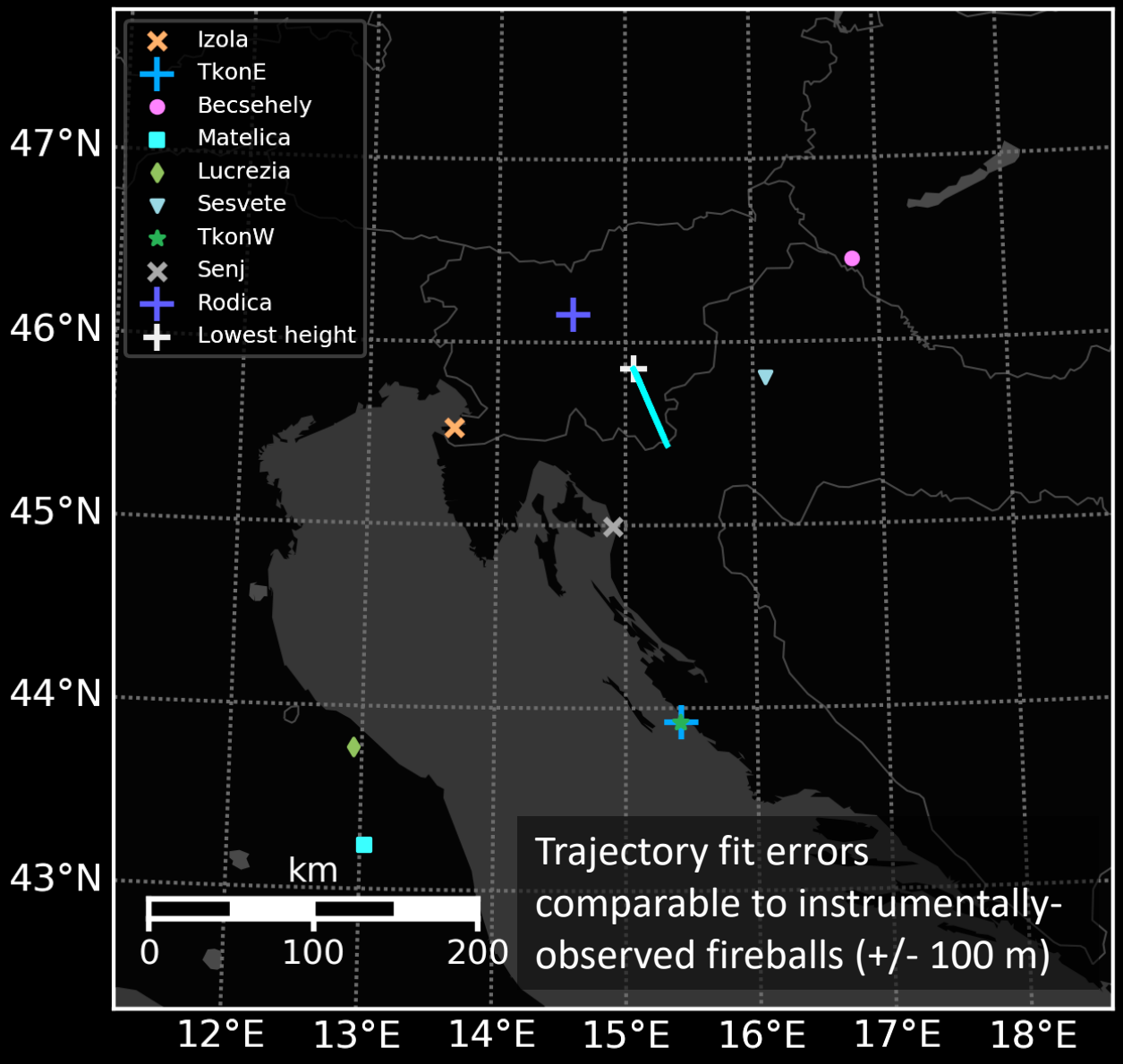
RIGHT CLICK - Remove pair
CTRL + SCROLL - Aperture radius adjust
CTRL + Z - Fit stars
CTRL + SHIFT + Z - Fit with initial distortion params set to 0
L - Astrometry fit details
P - Photometry fit
x=1429.34 y= 320.38 Intens= 255, Azim=267.00 Alt= 20.45 (date), RA=242.76 Dec=+12.55 (J2000)
SkyFit
ManualReduction

Reconstructed trajectory and orbit



Orbit:

$q = 0.5682 \pm 0.0005$ AU
$e = 0.6095 \pm 0.0007$
$i = 8.777 \pm 0.021°$
$\omega = 82.76 \pm 0.11°$
$\Omega = 338.993019$

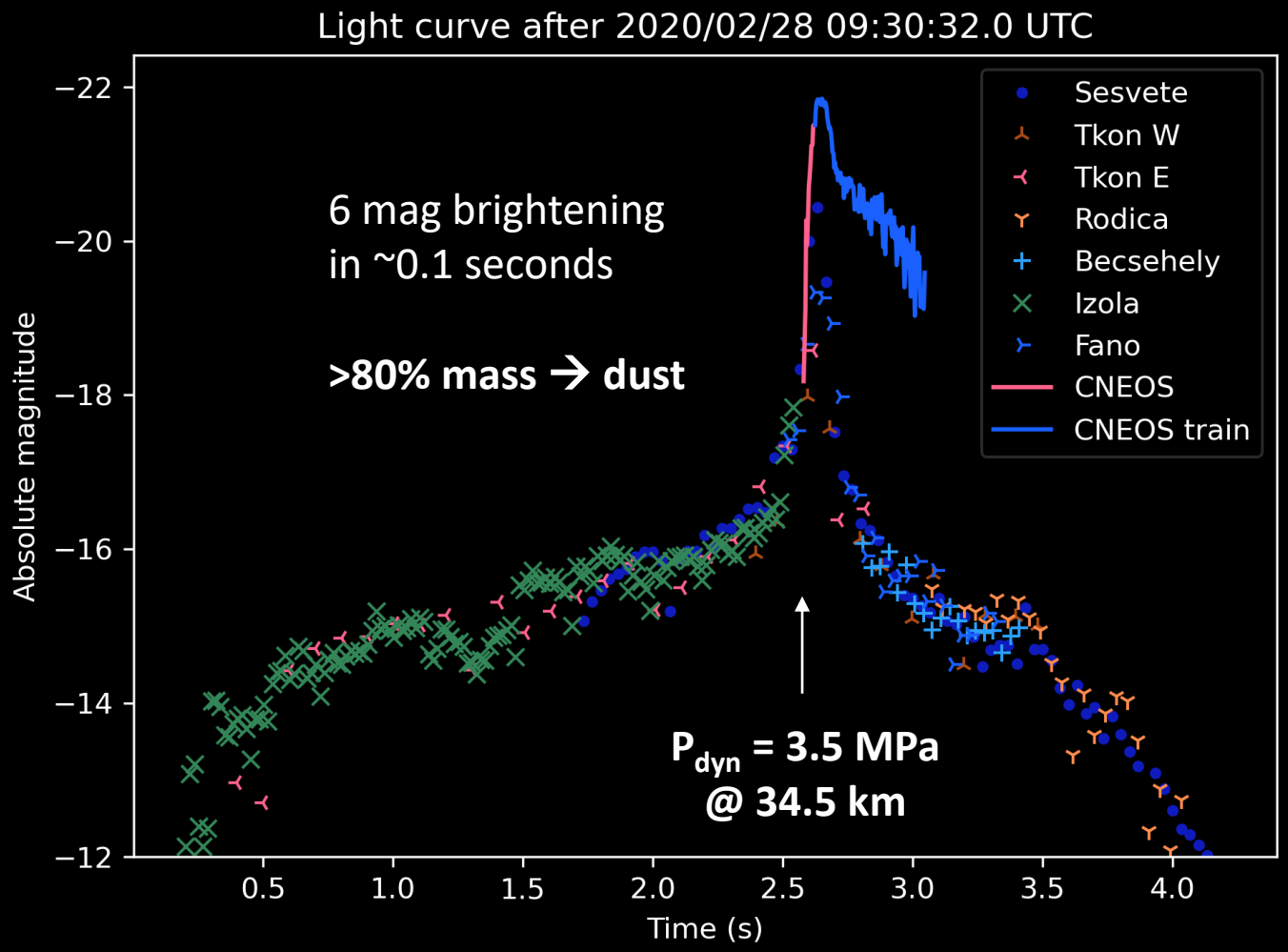
Source region: inner-main belt

(definitely not from the Gefion family)

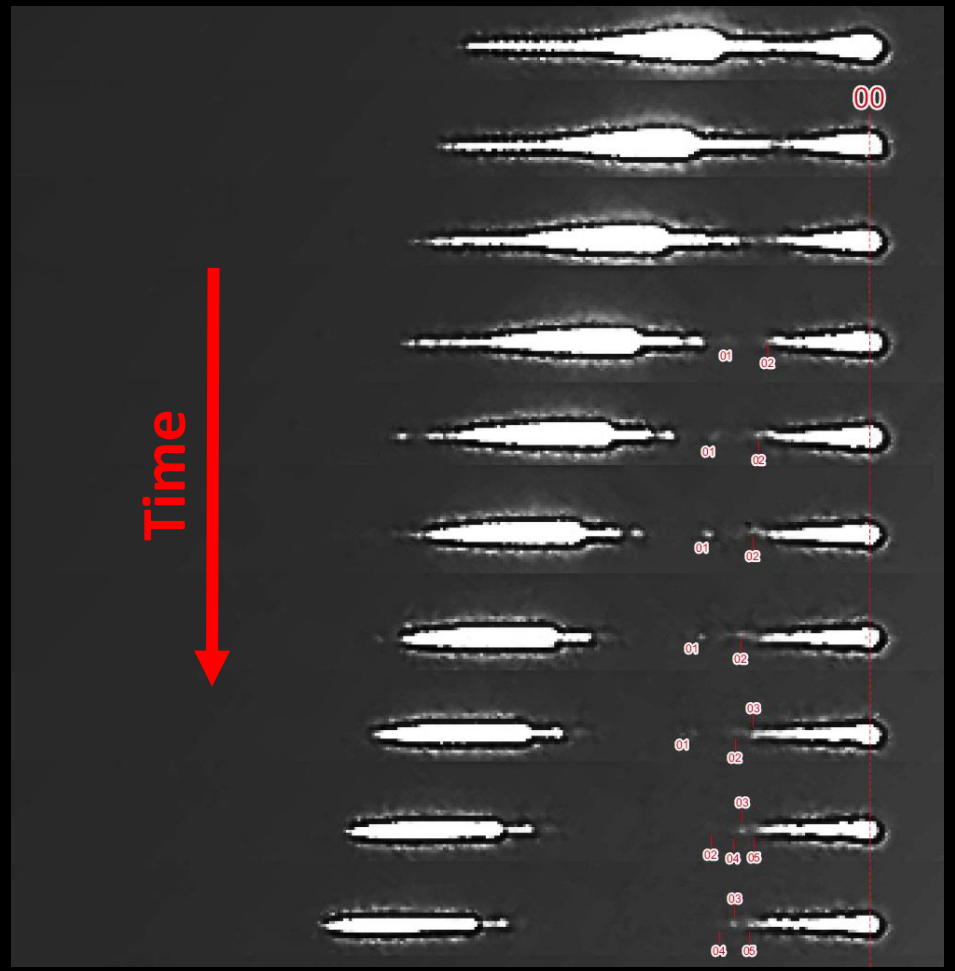
υ_6 resonance	75–89%
3:1 resonance	4–16%
Hungaria	2–12%
5:2 resonance	1–4%

Energy deposition for Novo Mesto

- USG/CNEOS data includes the luminous train (0.34 kt)



Luminous dust >> meteoroid



Fragmentation model fit

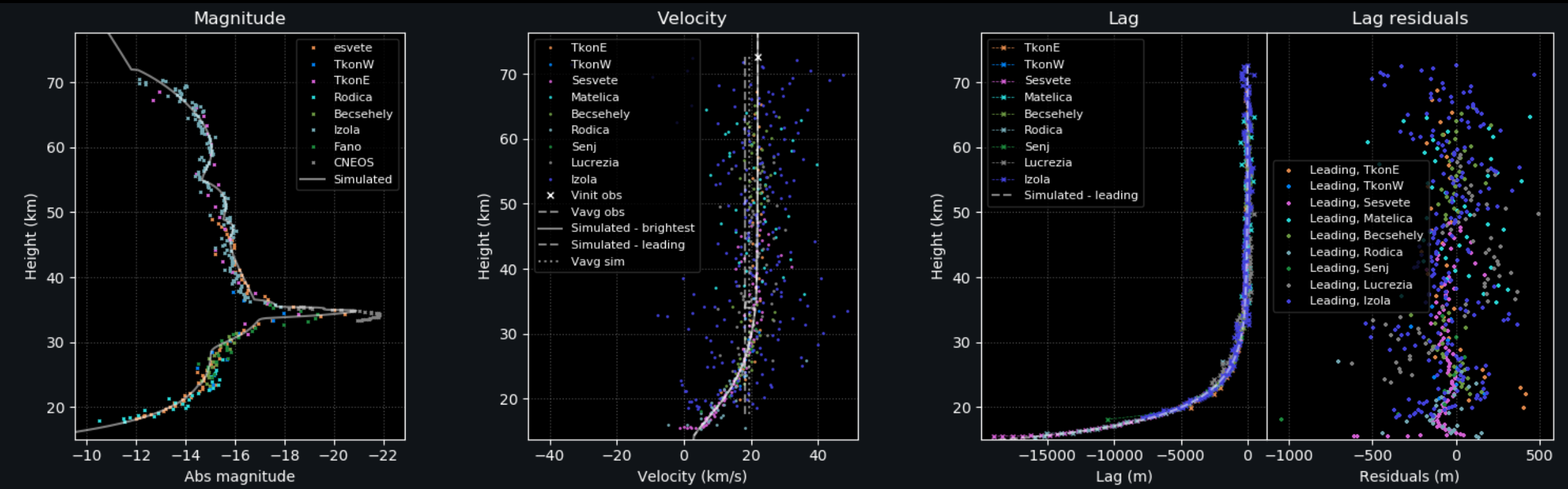
- Dynamics → accurate inversion - no deceleration until ~35 km

m_0 ≈ 3000 kg, ~1 m diameter

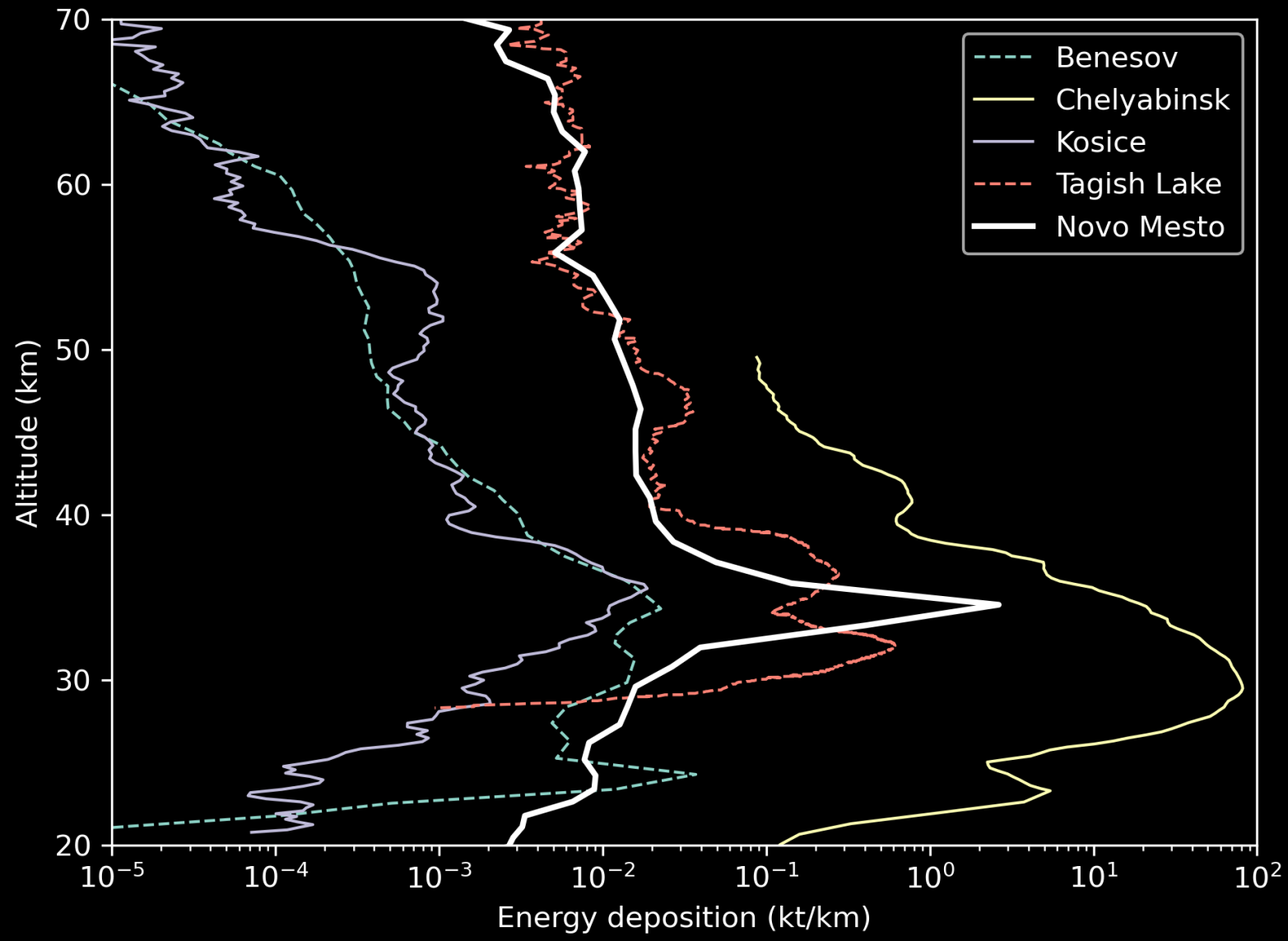
Bulk density = 3400 kg/m^3

Main fragmentation: ~3.5 MPa (2500 kg into mm-sized dust)

Minor fragmentations: 0.2 – 0.6 MPa (20 – 70 kg fragments)



New object class: “Bunker buster” fireball



Peak overpressure outsized for object size

Catastrophic structural failure at single point at a high dynamic pressure

<u>Best analogy:</u>
Weak concrete made only of sand and small gravel

Takeaways

- Currently unknown: Structural composition of impactors
- Developed: Open-source method for calibrating casual fireball videos and images
- Accurate structural model = High-resolution video + dynamics
- Novo Mesto superbolide - a new “bunker buster” class
  - Deposits ~90% of energy in a single deep disruption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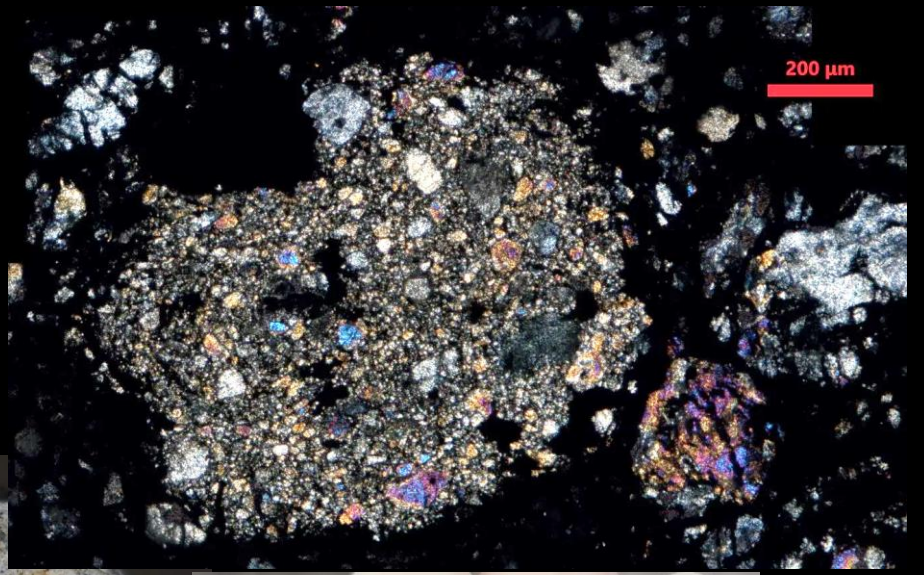
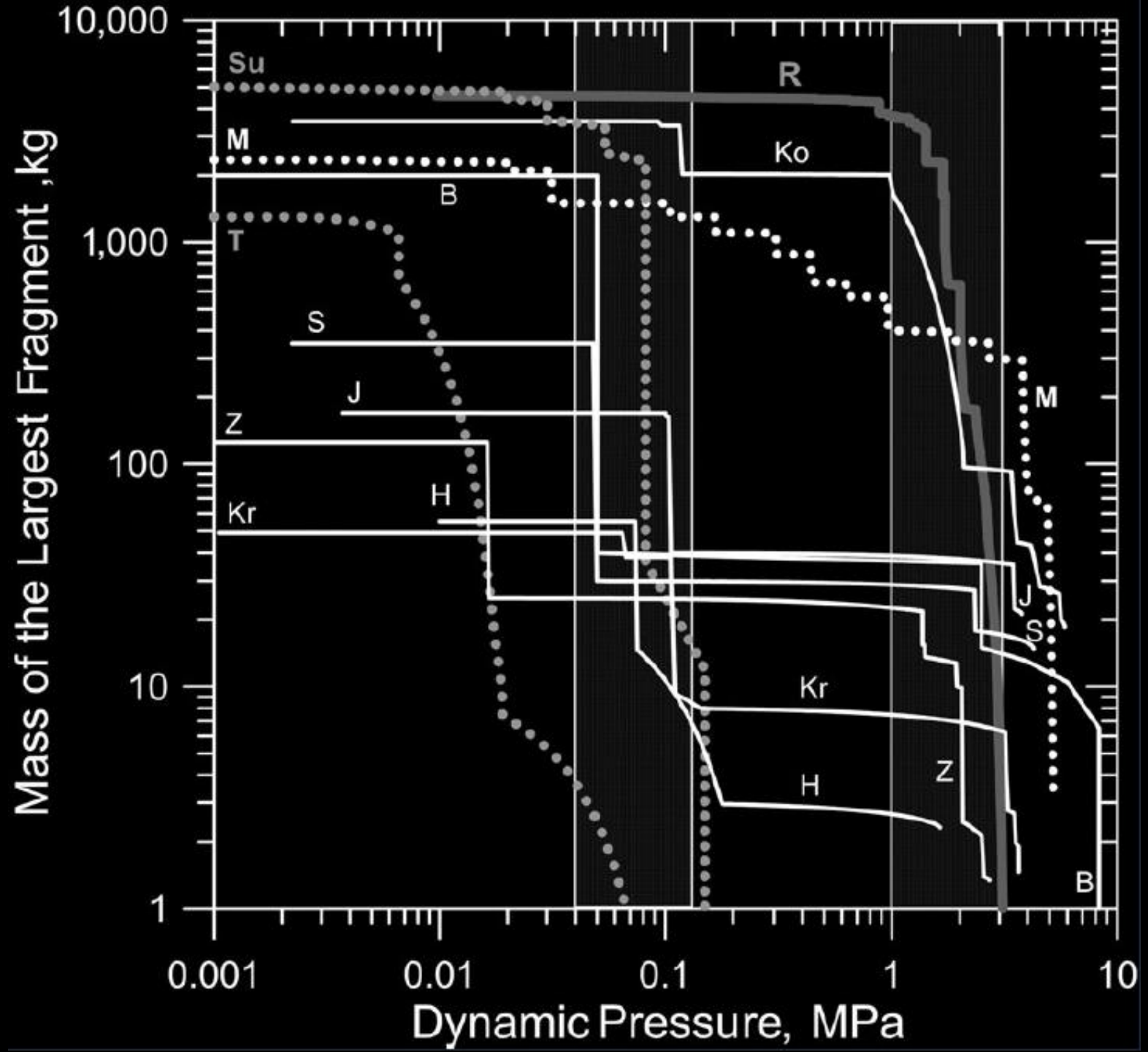
07 09 15
08 14 16
07 09 15
08 11 14 16
07 09 15
08 11 13 14 17 16
07 09,10 15
10 11 13 14 17 16
09 12 15
10 11 13 14 17 16
09 12 15

Backup slides

Meteorites

- Recovered by locals under the fireball's path within 2 weeks
- L5 chondrite, S5 shock stage, W0/1 weathering grade
- Brecciated and composed of several types of clasts in a fine-grained matrix
- Most chondrules are fractured, displaced

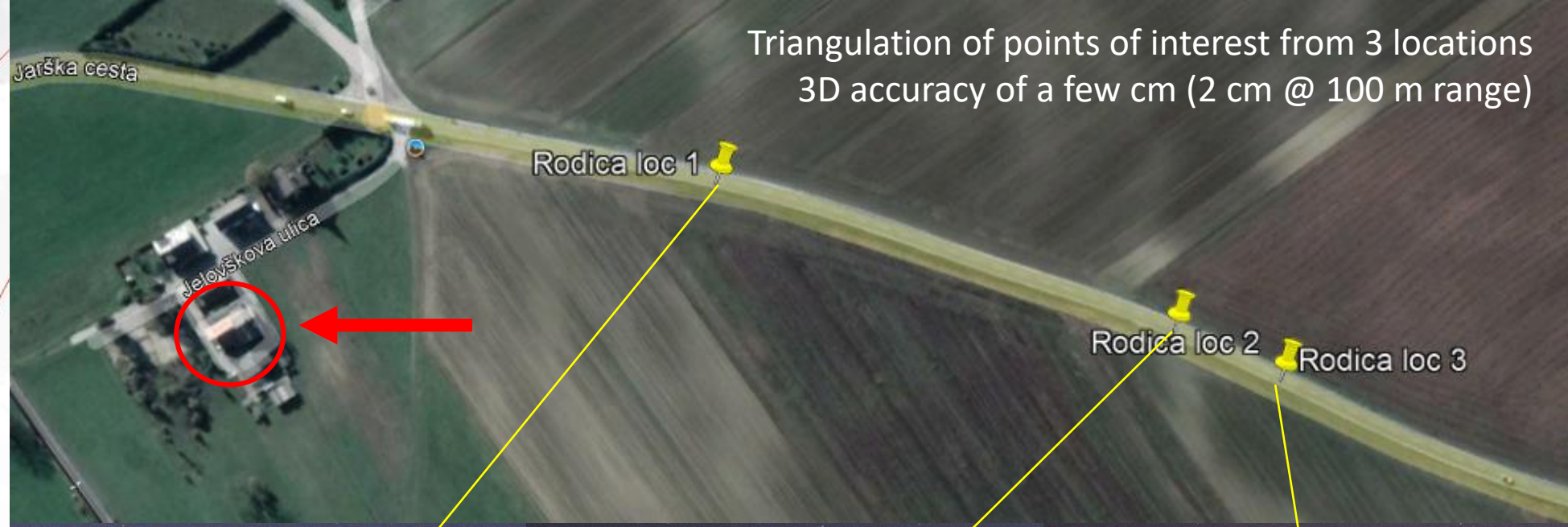


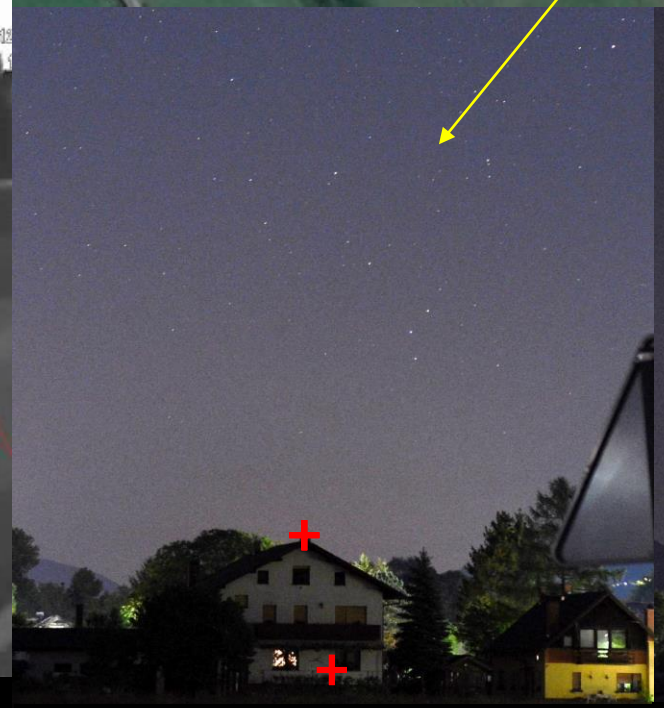


Borovička, J., Macke, R. J., Campbell-Brown, M. D., Levasseur-Regourd, A. C., Rietmeijer, F. J., & Kohout, T. (2019). Physical and chemical properties of meteoroids. *Meteoroids: Sources of Meteors on Earth and Beyond*, 37.

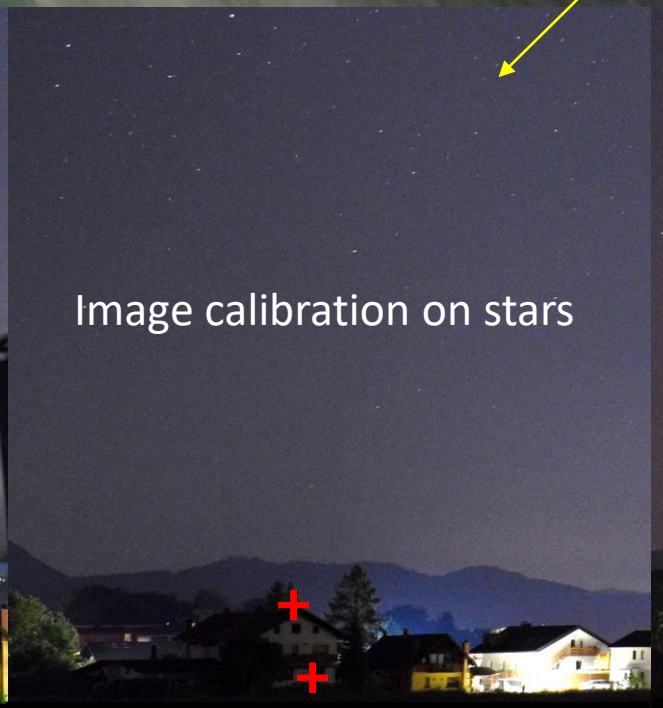
Triangulation of points of interest from 3 locations
3D accuracy of a few cm (2 cm @ 100 m range)

Dashcam video

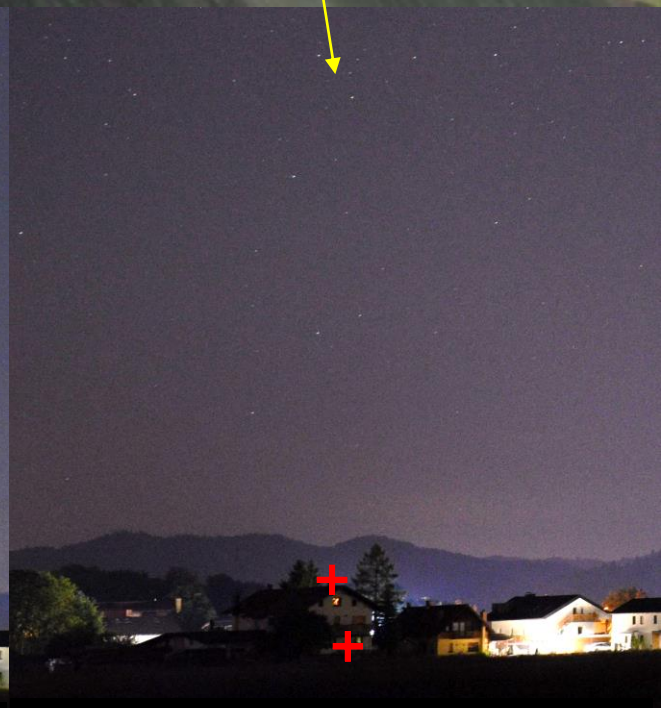




Loc 1



Loc 2



Loc 3

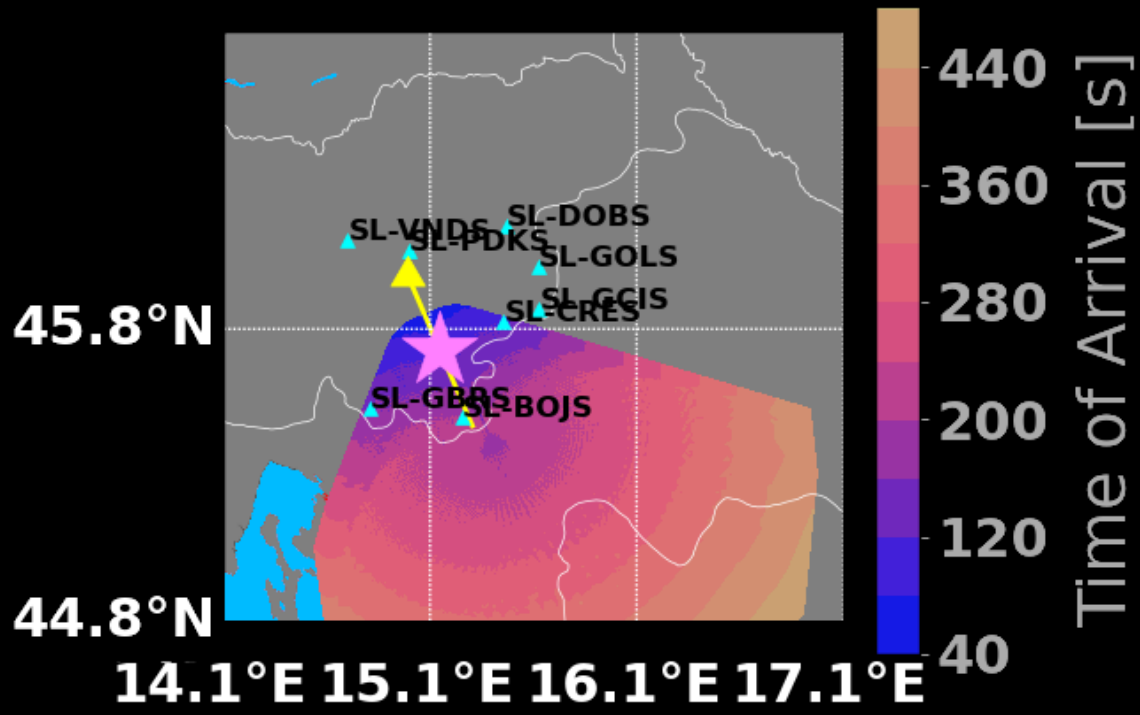
Ground-based observations

- Pros:
  - Dedicated fireball networks
  - Accurate dynamics
  - Resolving individual fragments and modes of fragmentation

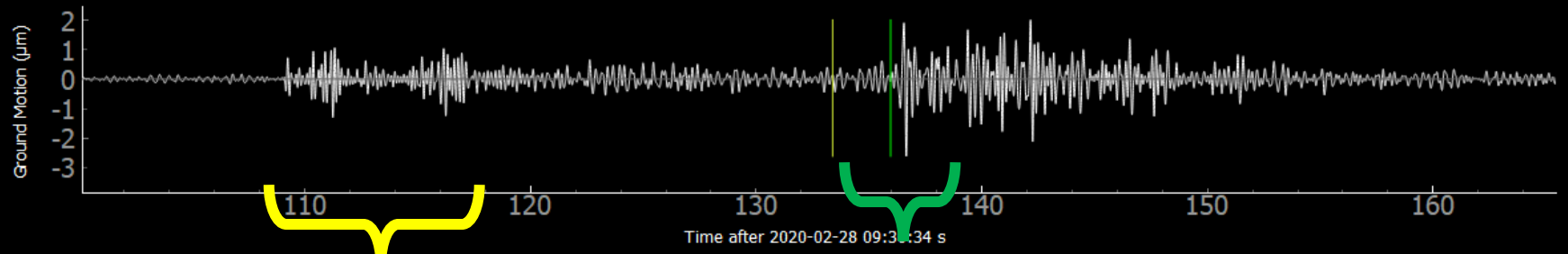
- Cons:
  - Large objects rare
  - Large objects saturate sensors → Hard to invert an unsaturated energy deposition
  - Only casual data often available

Seismic data

- Fragmentation (point source) heard by 8 seismic stations
- Ballistic (cylindrical) wave heard by SL-BOJS
- Arrivals 10 s of seconds earlier may be from seismic propagation (precursor waves)



Contour shows expected arrival times from the ballistic source



Precursor?

Consistent with Fragmentation at 35 km